PERMAFROST

BY

ROBERT F. BLACK
Geologist, United States Geological Survey

FROM THE SMITHSONIAN REPORT FOR 1950, PAGES 273–301
(WITH 12 PLATES)

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[With 12 plates]

Permafrost (perennially frozen ground) is a widespread geologic phenomenon whose importance and ramifications are rapidly becoming better known and more clearly understood. For many decades European scientists have been describing surficial features produced by frost action and permafrost, but for the most part they have given only passing reference to the perennially frozen ground. The current problem is to understand permafrost in order to evaluate it in the light of any particular endeavor, whether practical or academic. To understand permafrost we need a precise, standardized terminology, a comprehensive classification of forms, a systemization of available data, and coordination of effort by geologists, engineers, physicists, botanists, climatologists, and other scientists in broad research programs. These objectives are only gradually being realized.

This paper is largely a compilation of or reference to recent available literature. Its purpose is to make information more generally available concerning some of the many ramifications and practical applications of permafrost. New data from unpublished manuscripts in the files of the United States Geological Survey also are included where appropriate for clarity or completeness. Inna V. Poiré, of the United States Geological Survey, has prepared numerous condensations of Russian papers on permafrost and made them available to the author. Others were made available through the National Military Establishment. The library of the Engineers School, the Engineer Center, Fort Belvoir, Va., has many abstracts, condensations, and translations of Russian works that are available to civilian readers. References in this paper generally are only to the later American or German works, as most contain accounts of the earlier literature. The bulk of the literature, unfortunately, is in Russian and unavailable to the average reader, but some of it has been summarized by Muller (1945). A list of 190 titles of Russian articles dealing with permafrost is given by Weinberg (1940). The Arctic Insti-

[1] Published by permission of the Director, U. S. Geological Survey. Reprinted by permission from Trask's Applied Sedimentation, published by John Wiley & Sons, Inc., 1950. Minor modifications have been made, and some new references have been added by the author, but no attempt has been made to revise the paper completely or to list all new permafrost papers.

tute of North America (Tremayne, 1948) is currently preparing an annotated bibliography of all Arctic literature, including permafrost.

The multitude of problems associated with frost action, as we refer to it in the United States, appropriately should accompany any discussion of permafrost. However, lack of space permits only a passing reference to the relationship of permafrost to frost action. An annotated bibliography on frost action has been prepared by the Highway Research Board (1948).

Thanks are due Louis L. Ray, P. S. Smith, Inna V. Poiré, Troy L. Péwé, David M. Hopkins, William S. Benninghoff, Joel H. Swartz, and D. J. Cederstrom, of the United States Geological Survey, and to Stephen Taber and Kirk Bryan for critical reading of this manuscript. These and others in the Geological Survey have provided many valuable suggestions for which individual acknowledgment is difficult. The use of unpublished manuscripts and notes of P. S. Smith and C. V. Theis is greatly appreciated.

PERMAFROST

The term "permafrost" was proposed and defined by Muller (1945). A longer but more correct phrase is "perennially frozen ground" (Taber, 1943a). The difficulties of the current terminology are presented by Bryan (1946a, 1946b), who proposed a new set of terms. These are discussed by representative geologists and engineers (Bryan, 1948). Such terms as cryopedology, congeliturbation, congelifraction, and cryoplanation have been accepted by some geologists (Denny and Sticht, unpublished manuscript; Judson, 1949; Cailleux, 1948; Troll, 1948) in order to attempt standardization of the terms regarding perennially frozen ground and frost action. The term permafrost has been widely adopted by agencies of the United States Government, by private organizations, and by scientists and laymen alike. Its use is continued here because it is simple, euphonious, and easily understood by all.

Extent.—Much of northern Asia and northern North America contains permafrost (fig. 1) (Jenness, 1949; Sumgin, 1947; Muller, 1945; Obruchev, 1945; Troll, 1944; Taber, 1943a; Cressey, 1939; and others).

The areal subdivision of permafrost into continuous, discontinuous, and sporadic bodies is already possible on a small scale for much of Asia, but as yet for only part of North America. Refinements in delineations of these zones are being made each year. The southern margin of permafrost is known only approximately, and additional isolated bodies are being discovered as more detailed work is undertaken. The southern margin of permafrost has receded northward within the last century (Obruchev, 1946).

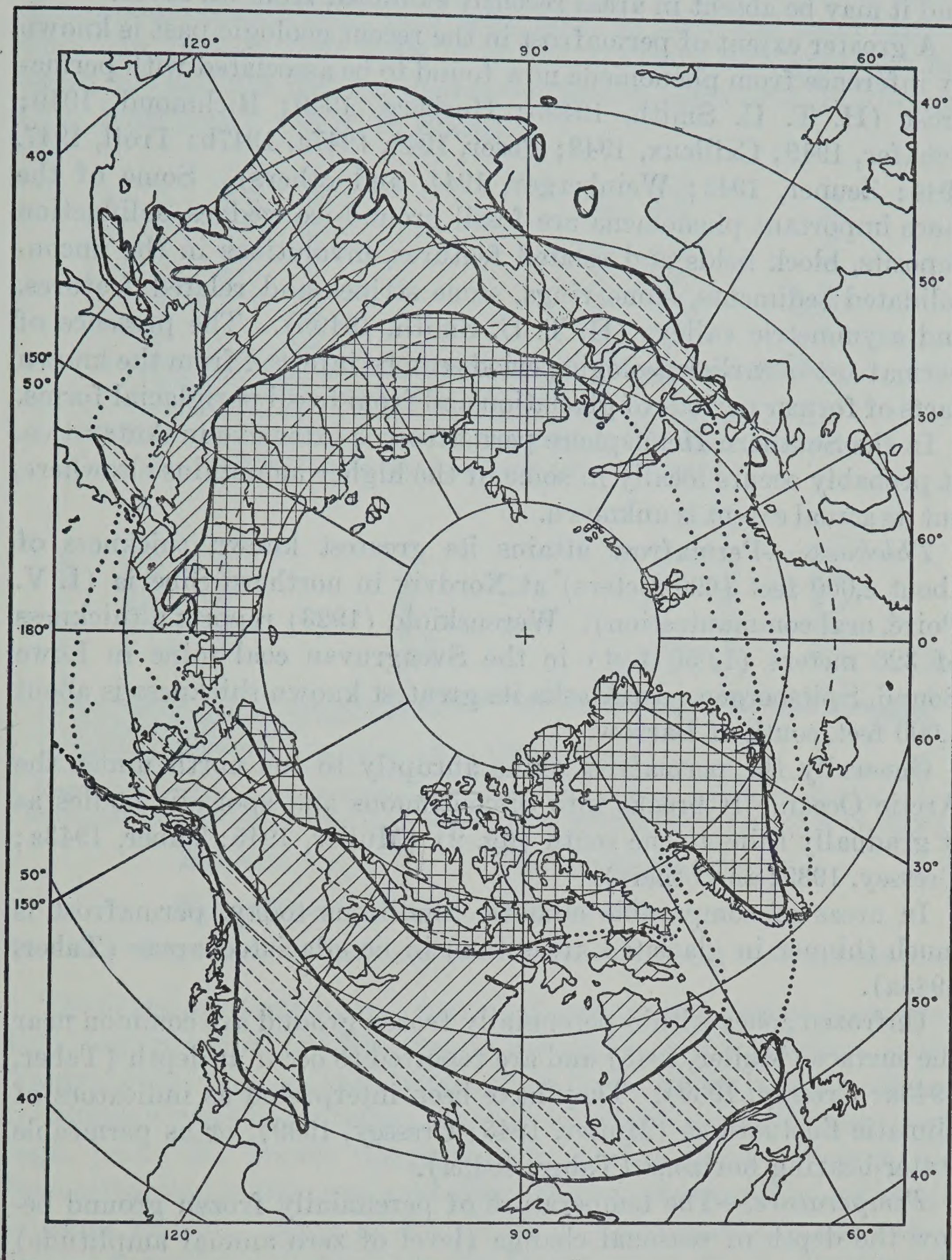


FIGURE 1.—Areal distribution of permafrost in the Northern Hemisphere.

Double hatching: Approximate extent of continuous permafrost. Ground temperature at a depth of 30 to 50 feet generally below —5° C. Diagonal hatching: Approximate extent of discontinuous permafrost. Ground temperature in permafrost at a depth of 30 to 50 feet generally between —5° and —1° C. Dotted diagonal hatching: Approximate extent of sporadic permafrost. Ground temperature in permafrost at a depth of 30 to 50 feet generally above —1° C. Reliability: Eurasia, good; Alaska, fair; all other, poor. (Eurasia after Sumgin and Petrovsky, 1940, courtesy of I. V. Poiré.)

Permafrost is absent or thin under some of the existing glaciers, and it may be absent in areas recently exhumed from ice cover.

A greater extent of permafrost in the recent geologic past is known by inference from phenomena now found to be associated with permafrost (H. T. U. Smith, 1949b; Horberg, 1949; Richmond, 1949; Schafer, 1949; Cailleux, 1948; Poser, 1948, 1947a, 1947b; Troll, 1947, 1944; Zeuner, 1945; Weinberger, 1944, and others). Some of the more important phenomena are fossil ground-ice wedges, solifluction deposits, block fields and related features, involutions in the unconsolidated sediments, stone rings, stone stripes and related features, and asymmetric valleys (H. T. U. Smith, 1949b). The presence of permafrost in earlier geologic periods can be inferred from the known facts of former periods of glaciation and from fossil periglacial forms.

In the Southern Hemisphere permafrost is extensive in Antarctica. It probably occurs locally in some of the higher mountains elsewhere, but its actual extent is unknown.

Thickness.—Permafrost attains its greatest known thickness of about 2,000 feet (620 meters) at Nordvik in northern Siberia (I. V. Poiré, oral communication). Werenskiold (1923) reports a thickness of 320 meters (1,050 feet) in the Sveagruvan coal mine in Lowe Sound, Spitsbergen. In Alaska its greatest known thickness is about 1,000 feet, south of Barrow.

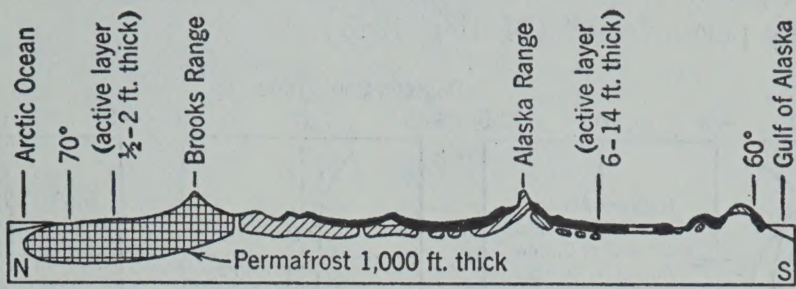
Generally the permafrost thins abruptly to the north under the Arctic Ocean. It breaks into discontinuous and sporadic bodies as it gradually thins to the south (fig. 2) (Muller, 1945; Taber, 1943a; Cressey, 1939; and others).

In areas of comparable climatic conditions today, permafrost is much thinner in glaciated areas than in nonglaciated areas (Taber, 1943a).

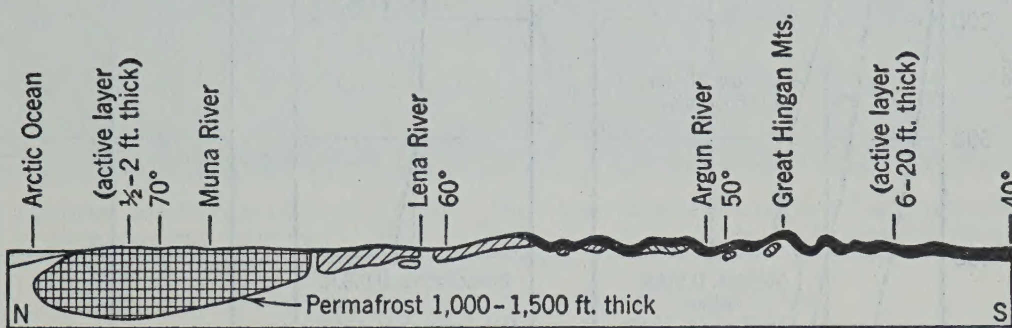
Unfrozen zones within perennially frozen ground are common near the surface (Muller, 1945) and are reported to occur at depth (Taber, 1943a; Cressey, 1939). They have been interpreted as indicators of climatic fluctuations (Muller, 1945; Cressey, 1939), or as permeable water-bearing horizons (Taber, 1943a).

Temperature.—The temperature of perennially frozen ground below the depth of seasonal change (level of zero annual amplitude) (Muller, 1945) ranges from slightly less than 0° C. to about −12° C. (I. V. Poiré, oral communication). In Alaska the minimum temperature recorded to date is −9.6° C. at a depth of 100 to 200 feet in a well about 40 miles southwest of Barrow (J. H. Swartz, 1948, written communication). Representative temperature profiles in areas of (1) continuous permafrost are shown in figure 3, *a*; of (2) discontinuous permafrost, figure 3, *b*; and of (3) sporadic bodies of permafrost, figure 3, *c*.

Temperature gradients from the base of permafrost up to the depth of minimum temperature vary from place to place and from time to time. In 1947–48 four wells in northern Alaska had gradients between 120 and 215 feet per degree centigrade (data of J. H. Swartz, G. R. MacCarthy, and R. F. Black).



Diagrammatic cross section through Alaska, along long. 150°, showing approximate distribution of permafrost and thickness of active layer



Diagrammatic cross section through Asia, along long. 120°, showing approximate distribution of permafrost and thickness of active layer. (Modified from unpublished cross section by I.V. Poire'.)

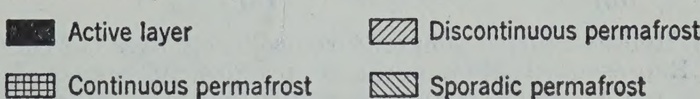


FIGURE 2.—Representative cross sections of permafrost areas in Alaska and Asia.

The shape of a temperature curve indicates pergelation or depergelation (aggradation or degradation of permafrost) (Muller, 1945; Taber, 1943a). Some deep temperature profiles have been considered by Russian workers to reflect climatic fluctuations in the recent geologic past. No known comprehensive mathematical approach has been attempted to interpret past climates from these profiles, although it seems feasible. Some of the effects of Pleistocene climatic variations on geothermal gradients are discussed by Birch (1948) and Ingersoll et al. (1948).

Character.—Permafrost is defined as a temperature phenomenon, and it may encompass any type of natural or artificial material, whether organic or inorganic. Generally permafrost consists of variable thicknesses of perennially frozen surficial unconsolidated materials, bedrock, and ice. Physical, chemical, or organic composition, degree of induration, texture, structure, water content, and the like range widely and are limited only by the extremes of nature or the

caprice of mankind. For example perennially frozen mammals, rodents, bacteria, artifacts, beds of sand and silt, lenses of ice, beds of peat, and varied junk piles, such as kitchen-middens, mine dumps, and ships' refuse heaps are individual items that collectively can be lumped under the term permafrost.

Ground perennially below freezing but containing no ice has been called "dry permafrost" (Muller, 1945).

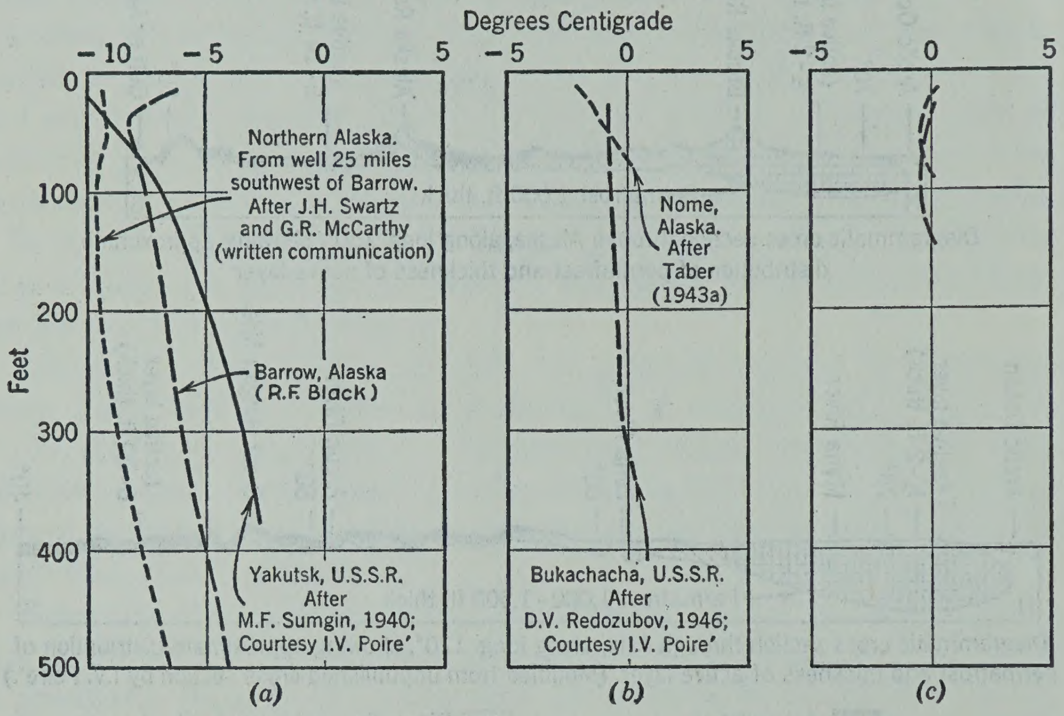


FIGURE 3.—(*a*) Representative temperature profiles in areas of continuous permafrost. (*b*) Representative temperature profiles in areas of discontinuous permafrost. (*c*) Hypothetical temperature profiles in areas of sporadic permafrost.

Permafrost composed largely of ice is abundant particularly in poorly drained fine-grained materials (pls. 1, 2, and 3). The ice occurs as thin films, grains, fillings, veinlets, large horizontal sheets, large vertical wedge-shaped masses, and irregular masses of all sizes. Many masses of clear ice are arranged in geometric patterns near the surface, that is, polygonal ground (pl. 4) and honeycomb structure. The ice may be clear, colorless, yellow, or brown. In many places it contains numerous oriented or unoriented air bubbles (pl. 5, fig. 1), and silt, clay, or organic materials. Size, shape, and orientation of the ice crystals differ widely (pl. 5, fig. 2). Discordant structures in sediments around large masses of ice are evidences of growth (Taber, 1943a; Leffingwell, 1919).

Relation to terrain features.—In the continuous zone of permafrost the upper limit (permafrost table, Muller, 1945) is generally within a few inches to 2 feet of the surface. Large lakes and a few large rivers lie in thawed areas slightly larger than the basins they occupy

1. Ground ice in the form of an ice wedge and in undifferentiated types exposed in a sea-cut silt bank 23 feet high, about 75 miles southeast of Barrow, Alaska. Photographed August 7, 1950.

(All photographs by the author unless otherwise stated.)

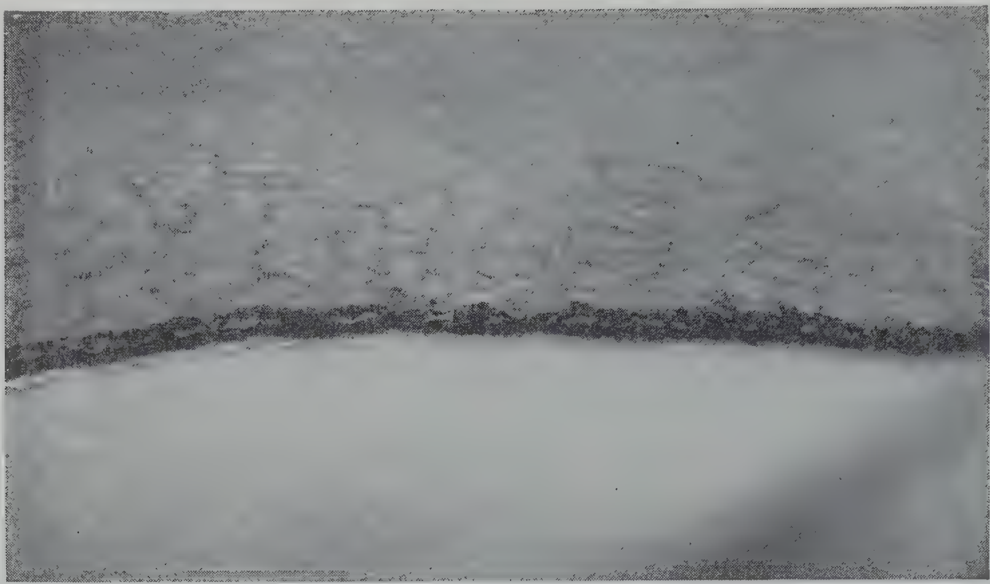
2. Irregular masses of ice and ice wedges exposed by placer operations in "muck" deposits at Fairbanks Creek, Fairbanks, Alaska. Photographed July 12, 1948.

1. Horizontal layer of blue ice and vertical ice wedge exposed by placer operations in "muck" deposits in Fairbanks Creek, Fairbanks, Alaska. Photographed July 12, 1948.

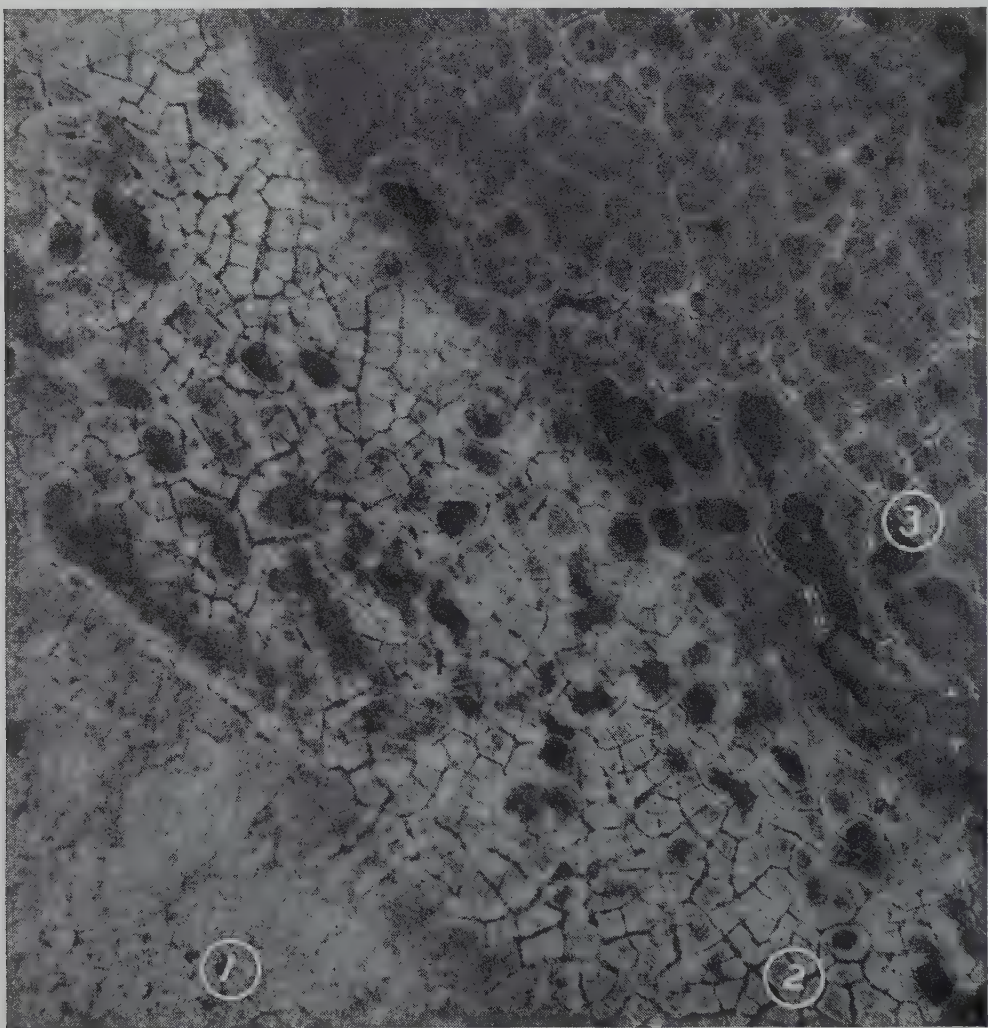
2. Three horizons of buried young trees in "muck" with considerable ice exposed by placer operations on Fairbanks Creek, Fairbanks, Alaska. Photographed July 12, 1948.

1. Thin veinlets, granules, and large mass of clear ice in organic-rich silt deposit near Barrow, Alaska. Photographed July 31, 1947.

2. Large individual crystals of ice in permafrost at a depth of about 20 feet in "muck" exposed by placer operations at Fairbanks Creek, Fairbanks, Alaska. Photographed July 2, 1950.

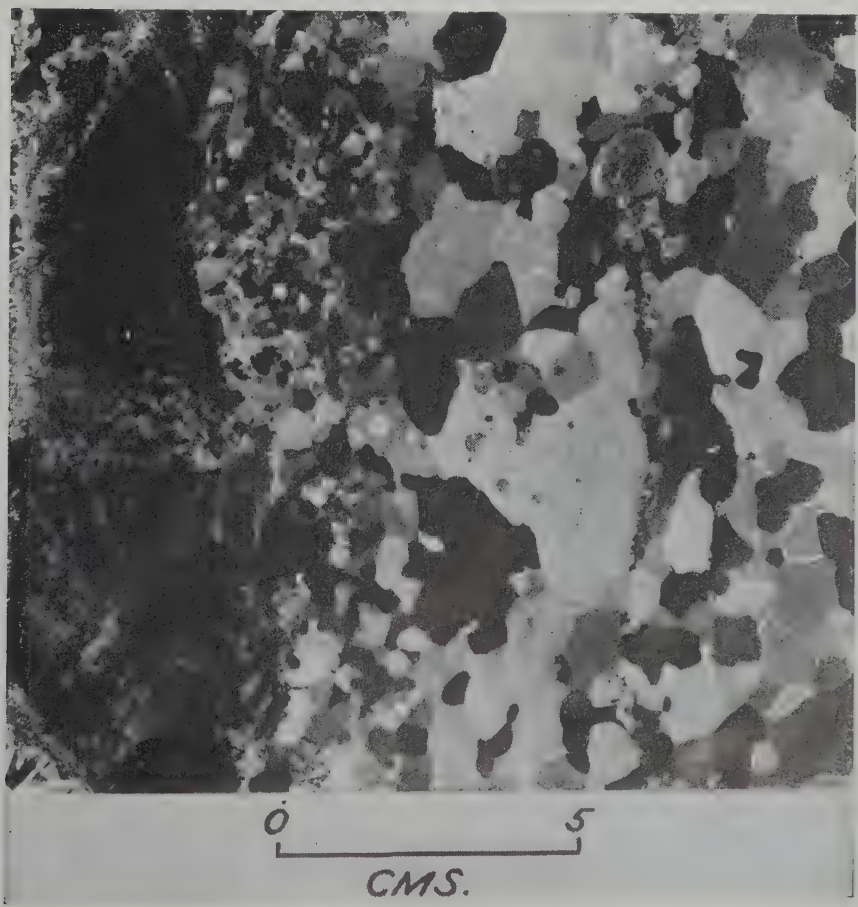


1. Ice-wedge polygons and ground ice in 15-foot sand bank exposed by wave action on the south side of Admiralty Bay, about 45 miles southeast of Barrow, Alaska. Photographed August 28, 1947.



2. Ice-wedge polygons of three distinct stages in surficial expression on coastal plain near Barrow, Alaska. Zone 1, containing high-centered polygons, is oldest; zone 2 is intermediate to zone 3, the youngest, with low-centered polygons. Photographed July 20, 1947, by the U. S. Coast and Geodetic Survey.

1. Thin section of ground ice from an ice wedge near Barrow, Alaska, showing numerous air bubbles. Photographed January 23, 1950.



2. Thin section of ground ice from an ice wedge near Barrow, Alaska, showing silt and individual ice crystals by using transmitted light and crossed polaroids. Photographed April 21, 1950.

1. Soil creep in solifluction lobes on rounded hill at "12-mile Summit" on Steese Highway, about 87 miles by road northeast of Fairbanks, Alaska. Photographed July 5, 1948.

2. Landslide on top of thawing permafrost on Slana-Tok Cut-off, 27.9 miles from Gakona in east-central Alaska. Photographed July 9, 1946.

1. Ice laccoliths (small ground-ice mound, small pingo, or frost blister) produced by the heaving of the active layer by the hydrostatic pressure of water trapped between downward-progressing seasonal frost and permafrost in a swampy lake bed, near Barrow, Alaska. Four inches of moss and other vegetation covers a plano-convex disk about 15 inches thick and 5 feet in diameter. Photographed October 4, 1949.

2. Peat mound (frost mound), partially dissected by slumping along a lake about 25 miles southeast of Barrow, contains several bodies of clear ice underlying peat. The ice was introduced in part by filling by sublimation in horizontal contraction cracks and in part by forceful injection of water along a zone between the active layer and permafrost. Photographed August 21, 1946.

1. Thermokarst or cave-in lake about 10 miles east of Mentasta Lake on the Slana-Tok Cut-off in east-central Alaska. Photographed July 9, 1946.

2. Pingo, estimated 60 feet high, on the coastal plain of northern Alaska, about 30 miles north of Umiat, Alaska. Photographed September 17, 1945.

1. Caving polygons near Barrow, with relief of 4 to 8 feet, resulting from the thawing of ice wedges after the protecting mat of tundra vegetation has been removed. Photographed August 25, 1947.

2. Ground ice in foundation excavation near Barrow. Concrete in forms is being heated to permit setting on top of permafrost. Photographed July 15, 1947.

Upper: Left, irregular settling of Kougarok Railroad on frozen tundra about 7 miles north of Nome, Alaska; photographed August 10, 1948. Right, caving and irregular settling in gravel fill over thawing ice wedges in runway at Umiat, Alaska; photographed August 30, 1946.
Lower: Left, road icing, about 4 feet thick, on Slana-Tok Cut-off about 58.7 miles north of Slana in east-central Alaska; photographed February 27, 1946. Right, earth mounds 4 to 8 feet high produced by stripping of vegetation in farming and subsequent thawing of ice wedge polygons near College, Alaska; photographed September 19, 1948.

1. Bridge piling on the Alaska Railroad broken by downhill creep in mud on top of permafrost in the Nenana River Gorge, central Alaska. Photographed September 24, 1948.

2. Slump in gravel on street in Barrow, where steam line produced thawing of permafrost. Photographed May 12, 1950.

1. Mud flow on top of permafrost along the Alaska Railroad resulting in track settling, near Moody, Alaska. Photographed June 22, 1948.

2. Settling cracks in foundation wall of the U. S. Post Office, Nome, Alaska, after thawing of permafrost under the building. Photographed August 10, 1948.

(Black and Barksdale, 1949; Muller, 1945). Well-drained coarse-grained materials may thaw annually to a depth of 6 feet. Poorly drained fine-grained materials protected from solar radiation and insulated with moss and other vegetation may thaw annually to a depth of only 4 inches.

In the discontinuous zone permafrost is absent under most major rivers and lakes. It may be absent in the tops of some well-drained low hills. Seasonal thaw (active layer, Muller, 1945) penetrates 1 foot to 10 feet, depending on insulation, insolation, drainage, and type of material.

Sporadic bodies of permafrost may be relics below the active layer or may be forming in favorable situations in poorly drained fine-grained materials on north-facing slopes. In the zone of sporadic permafrost the active layer may or may not reach the permafrost table, and it ranges between 2 and 14 feet in thickness.

Generally the depth of thaw is at a minimum in northern latitudes and increases to the south. It is at a minimum in peat or highly organic sediments and increases successively in clay, silt, and sand to a maximum in gravelly ground or exposed bedrock. It is less at high altitudes than at low altitudes; less in poorly drained ground than in dry well-drained ground; at a minimum under certain types of tundra and increases successively in thickness under areas of bog shrubs, black spruce, larch, white spruce, birch, aspen, and poplar to a maximum under tall pines. It is less in areas of heavy snowfall; less in areas with cloudy summers; and less on north-facing slopes (Muller, 1945; Troll, 1944; Taber, 1943a; and others).

Works of man commonly upset the natural thermal equilibrium and may tend to destroy permafrost or to aid in its formation. Most roads, runways, and other structures on the surface of or in the ground generally have lower permafrost tables than undisturbed natural areas adjacent to them. Structures above the ground and insulated from the ground protect the surface from solar radiation and commonly produce higher permafrost tables.

Origin.—The origin of perennially frozen ground is discussed by Jenness (1949), Muller (1945), Zeuner (1945), Taber (1943a), Cressey (1939), Nikiforoff (1932), Leffingwell (1919), and others. Generally it can be stated that most sporadic bodies of permafrost are relics of colder climates. Discontinuous bodies of permafrost are largely relics, but under favorable conditions may grow in size, and new deposits are being perennially frozen. In areas of continuous permafrost, heat is being dissipated actively from the surface of the earth to the atmosphere, and new deltas, bars, landslides, mine tailings, and other deposits are being pergelated (incorporated in the permafrost) (Bryan, 1946a).

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Local surface evidences indicate that heat, in some places at least, is being absorbed at the base of permafrost faster than it is being dissipated at the surface (Hopkins, 1949; Young, 1918). Hence the cold reserve is being lessened, and the thickness of permafrost is decreasing from the base upward.

The mean annual air temperature required to produce permafrost undoubtedly varies many degrees because of local conditions. Generally it is given as 30° to 24° F.; theoretically permafrost can form above 32° F. (Theis, unpublished manuscript), and apparently it is doing so locally in parts of southwest Alaska where poor drainage, abundant vegetation, cloudy summers, and low insolation are found (S. Abrahamson, oral communication, and Ernest H. Muller, written communication).

The relative effects of past climates have been inferred qualitatively through a study of present temperature profiles and indirectly through a study of past deposits, pollen analysis, vegetal changes, structural soils, and blockfields.

The origin of large, clear ice masses in the permafrost is a special problem in itself. Numerous theories are extant, and one or more may apply to a particular mass of ice (Taber, 1943a; Leffingwell, 1919; and others).

GEOLOGIC RAMIFICATIONS

Throughout the Arctic and sub-Arctic the role of permafrost is extremely important. As an impervious layer in continuous permafrost zones, it exerts a drastic influence on surface waters, completely prevents precipitation from entering the natural ground-water reservoirs, and commonly causes a concentration of organic acids and of mineral salts in suprapermafrost water. In discontinuous permafrost zones, and less so in areas of sporadic permafrost, ground-water movements are interrupted or channelized. Quality of water, too, can be materially affected by the storage for centuries and subsequent release by thawing of organic and inorganic materials (Kaliaev, 1947). In fact, our present conceptions of ground-water reservoirs, ground- and surface-water movements, infiltration, quality of water, and so on must be reevaluated in considering permafrost as a new geologic formation, generally not uniform in composition or distribution, that transcends all rock and soil formations. Furthermore, it must be considered as much in the light of past as of present conditions.

It is well known that in cold climates physical disintegration (frost-splitting, congelifraction) plays a more important role than chemical weathering. The repeated freezing of water-saturated materials and the growth of ice crystals in numerous small pores, cracks, joints, cleavage planes, or partings is by far the most effective destructive process. Taber (1943a) has shown that, without water, disintegration

is generally much slower. Permafrost is one of the most important agents in keeping the soils supersaturated (containing more water than pore space—a suspension) and in keeping many rock fragments wet.

It is less widely known that mass-wasting processes in the Arctic and sub-Arctic are instrumental in the transport of tremendous volumes of material. With the exception of unbroken bedrock, the materials on the surface of slopes greater than 1° to 3° are on the move everywhere in summer. The amount of material involved and the rapidity of such movements impress all who have studied them (Washburn, 1947, and others).

Permafrost, on thawing slightly in summer, supplies a lubricated surface and additional water to materials probably already saturated. Hence solifluction (pl. 6, fig. 1), mud flows (pl. 6, fig. 2), and other gravity movements take place with ease and, in favorable locations, even supply material to streams faster than the streams can remove it (Wahrhaftig, 1949, and others). Bryan (1949) has coined the term "cryoplanation" to cover such processes, including also frost-heaving normal to slopes and settling vertically, which in the Arctic are instrumental in reducing the landscape to long, smooth slopes and gently rounded forms. Such physiographic processes are only partly understood and their effects only qualitatively known (Bryan, 1949).

Permafrost, by aiding in maintaining saturated or supersaturated conditions in surficial materials, indirectly aids in frost-stirring (congeliturbation), frost-splitting, and mass-wasting processes so that, in places, bedrock is disintegrated, reduced in size, thoroughly mixed, and rapidly transported. The result is a silt-sized sediment that is widespread in the Arctic. Various authors (Bryan, 1949; Hopkins, 1949; P. S. Smith, unpublished manuscript; Zeuner, 1945; Taber, 1943a; Tuck, 1940) disagree as to whether some of the material is derived from eolian, lacustrine, or local frost-splitting and mass-wasting processes. Size-grade-distribution curves, mineral comparisons, chemical analyses, comparisons with glacial materials and with organic materials, etc., have been used by various investigators to prove their point, but the differences of opinion have by no means been resolved.

Frost action (frost-heaving, frost-stirring, and frost-splitting) and gravity movements result in many surface forms that are found most abundantly in areas of permafrost, i. e., *strukturboden*, involutions, frost boils, hummocks, altiplanation terraces, terrecettes, and soil stripes (Judson, 1949; Richmond, 1949; Schafer, 1949; H. T. U. Smith, 1949; Cailleux, 1948; Troll, 1948, 1947, 1944; Washburn, 1947, Conrad, 1946; Zeuner, 1945; Taber, 1943a; Sharp, 1942b; Gatty et al., 1942; Steche, 1933; Högbom, 1914; and others). Annual freezing in permafrost areas also forces changes in surface- and ground-water

migration and commonly results in pingos, frost blisters, ice mounds, icings, aufeis, and other related forms (Muller, 1945; Troll, 1944; Sharp, 1942a; Mullis, 1930). (Pl. 7 and pl. 8, fig. 2). Many of the forms produced by frost action and seasonal freezing are closely related in character and origin; however, the lack of a standardized terminology for these features produces a perplexing picture.

Little can be said quantitatively regarding the importance of frost action (and indirectly permafrost) in ancient sediments and soils (Zeuner, 1945). Throughout the world, deposits of former glaciers have been found in the stratigraphic column. They indicate many periods of glaciation and, hence, cold climates. Undoubtedly permafrost was present during those times. Fossil forms derived from frost and permafrost are known (Horberg, 1949; Judson, 1949; Richmond, 1949; Schafer, 1949; H. T. U. Smith, 1949b; Wahrhaftig, 1949; Zeuner, 1946, 1945; Troll, 1944; and others). These forms provide data on the processes producing the surficial materials and on the environment of deposition. These features are only now being recognized and studied in the detail that is warranted (Bryan, 1949).

Permafrost throughout the world has provided an outstanding wealth of material for paleontologists and archeologists (Hibben, 1941). In perennially frozen Alaskan placers alone, investigators have found more than 27 different plants (Chaney and Mason, 1936), including whole forests of buried stumps (Giddings, 1938); numerous iron and other bacteria; algae; 87 species of diatoms (Taber, 1943a); bones of at least 20 species of large mammals, represented by tens of thousands of specimens (Taber, 1943a; Wilkerson, 1932); numerous species of rodents; and a few species of mollusks, sponges, and insects (Taber, 1943a). Permafrost in Siberia has been a storehouse for Pleistocene mammals (Tolmachoff, 1929).

Permafrost upsets many readings taken by geophysicists in determining the internal constitution of the earth. Velocities of seismic waves, for instance, are materially increased by frozen ground containing much ice and may result in considerable errors in determinations of depths. Although the actual increases are not definitely known, they probably fall within the range of 1,000 to 8,000 feet per second (J. H. Swartz, oral communication). Unfortunately, the lower contact of permafrost causes, with present equipment, no satisfactory reflections or refractions. Seismic methods cannot be used to determine the thickness or variability of the zone distorting the seismic waves. Difficulties in drilling, preparing the explosive charges, checking the ground waves, and getting interpretable effects are augmented in permafrost areas.

Electrical methods, particularly the resistivity methods, have given promise of solving some of the difficulties in determining the extent

and thickness of permafrost (Enenstein, 1947; Swartz and Shepard, 1946; Muller, 1945; and Joestings, 1941). Generally resistivities of frozen silt and gravel are several thousand ohms higher than comparable unfrozen materials and may be 20 to 120 times as high (Swartz and Shepard, 1946; Joestings, 1941). However, it is well known that the type of material is less important than the amount of unfrozen ground water and dissolved salts within the material. Even in frozen ground these factors are so variable that resistivity data can be interpreted with reliability only by experienced men and generally only in areas where some positive checks can be made through drilling.

Sumgin and Petrovsky (1947) discuss a new radio-wave technique used where permafrost is below −5° C.

ENGINEERING SIGNIFICANCES

In Alaska during World War II the difficulties encountered by our armed forces in obtaining permanent water supplies and in constructing runways, roads, and buildings in permafrost areas focused attention on permafrost as nothing else could (Wilson, 1948; Jaillite, 1947; Barnes, 1946; Taber, 1943b). Only then did most people realize that in Russia similar difficulties with railroads, roads, bridges, houses, and factories had impeded colonization and development of the north for decades. Now with the recent progress in aviation, and because of the strategic importance of the north, active construction and settlement for military and civilian personnel must increase, and the problems of permafrost must be solved.

Fortunately we can draw on the vast experience of the Soviet Union. Their engineers have shown that it is—

> . . . a losing battle to fight the forces of frozen ground simply by using stronger materials or by resorting to more rigid designs. On the other hand, the same experience has demonstrated that satisfactory results can be achieved and are allowed for in the design in such a manner that they appreciably minimize or completely neutralize and eliminate the destructive effect of frost action . . . Once the frozen ground problems are understood and correctly evaluated, their successful solution is for the most part a matter of common sense whereby the frost forces are utilized to play the hand of the engineer and not against it. . . . it is worth noting that in Soviet Russia since about 1938 all governmental organizations, municipalities, and cooperative societies are required to make a thorough survey of the permafrost conditions according to a prescribed plan before any structure may be erected in the permafrost region. [Muller, 1945, pp. 1–2, 85–86.]

Specifically we must think of permafrost in construction of buildings, roads, bridges, runways, railroads, dams, and reservoirs, in problems of water supply, sewage disposal, telephone lines, drainage, excavation, ground storage, and in many other ways. Permafrost can be used as a construction material or as a base for construction, but steps

must be taken to insure its stability. Otherwise it must be destroyed and appropriate steps taken to prevent it from returning.

BIOLOGIC SIGNIFICANCES

Permafrost, by means of its low temperature and ability to prevent runoff, is a potent factor that aids in controlling vegetal growth in the Arctic and sub-Arctic (Mosley, 1937). Many places have semiarid climate yet have luxuriant growths of vegetation because the permafrost prevents the loss of precipitation through underground drainage (low evaporation is possibly as important). Such conditions are natural breeding environments for mosquitoes and other insects.

Conversely, luxuriant growths of vegetation, by insulating the permafrost in summer, prevent deep thawing and augment cold soil temperatures. Hence those species with deep root systems, such as certain trees, are dwarfed or absent, and nourishment available to smaller plants is limited.

Raup (1941, 1947) and Griggs (1936) point out that much of Arctic soil is unstable because of frost action (commonly associated with permafrost) and that standard biological methods describing plant communities do not apply. The normal associations have been greatly disturbed, special communities for different frost forms can be identified, and above all the plant communities must be described on the basis of their physical habitat.

Permafrost probably controls the distribution of some animal species, such as the frogs or toads, that require thawed ground into which they can burrow for the winter. Foxes can have dens only in dry elevated places where the depth of thaw is 2 feet or more. Similarly, permafrost affects worms, burrowing insects, and other animals that live in the ground.

Indirectly, permafrost, by exercising some control on types of vegetation, that is, tundra vs. forest, also determines the distribution of grazing animals such as the reindeer and Barren Ground caribou.

FACTORS AFFECTING PERMAFROST

Most major factors affecting permafrost are recognized qualitatively, but non is well known quantitatively. These factors are easily visualized by turning to the original definition of the term "permafrost." As permafrost is fundamentally a temperature phenomenon, we may think of it as a negative temperature produced by climate in material generally of heterogeneous composition. Permafrost is produced because, through a combination of many variables more heat is removed from a portion of the earth during a period of

two or more years than is replaced. Hence a cold reserve is established.

Basically the process can be reduced to one of heat exchange between the sun, the atmosphere, and the earth. The sun, through solar radiation (insolation), and the interior of the earth, primarily through conduction, supply practically all primary heat to the surface of the earth (biological processes, natural or artificial fires, chemical reactions, cosmic or other radiations excepted). This primary heat is dissipated to the atmosphere and to outer space by conduction, radiation, convection, and evaporation. The atmosphere, by warm winds and precipitation, also distributes secondary heat to the surface of smaller areas.

We know that earth temperatures at the depth of seasonal change are in most places within a few degrees of the mean annual air temperature, and that a geothermal gradient is established from the surface to the interior of the earth. The geothermal gradient at any one place is relatively fixed from year to year, though it varies from place to place and has changed markedly during geologic time. It is generally considered as 1° F. for each 60 to 110 feet of depth in sedimentary rock in the United States (Orstrand, 1939); possibly 0.1 to 0.2 calorie per square centimeter per day is transmitted to the surface from the interior. In contrast the sun supplies possibly as much as several hundred calories per square centimeter per day to the surface, depending primarily on the season and secondarily on cloudiness, humidity, altitude, latitude, and other factors. This period of rapid heating, however, is very short in the Arctic, and for many months heat is dissipated to the atmosphere and outer space. When dissipation of heat outweights input, a cold reserve is produced. If the cold reserve remains below freezing for more than 2 years, it is called permafrost.

Although the fundamental thesis of the problem is simple, its quantitative solution is exceedingly complex. In only a few isolated areas in the Arctic do we know anything of the geothermal gradients in and below permafrost. The climate (including insolation) is so incompletely known that at present it is not possible to evaluate climatic factors except in a general way as they effect primary or secondary heat or dissipation of heat (Lane, 1946, and others). Thus it is well known that the following conditions tend to produce permafrost:

1. Long, cold winters and short, cool summers.
2. Low precipitation the year around and especially low snowfall.
3. Clear winters and cloudy summers.
4. Rapid evaporation the year around.
5. Strong, cold winds in summer and winter.
6. Low insolation.

The materials involved have different specific heats and different heat conductivities (Shannon and Wells, 1947; Muller, 1945; W. O. Smith, 1942, 1939). Chemical and physical properties vary widely, yet are of primary importance (W. O. Smith, 1942; Taber, 1930a, 1930b). Water transmits heat about 25 times as fast as air, and ice 4 times as fast as water. Thus, poorly drained silt and muck are much more easily frozen than dry, coarse-grained gravel. W. O. Smith (1942) points out the marked effect of soil structures and of architecture of pore space on thermal resistance in natural soils.

The dissipating surface of the earth is even more complex and more changeable. Water-saturated frozen vegetation and soil (bare of snow) in winter is an active conductor, whereas lush dry vegetation and dry porous soil in summer is an excellent insulator. Black-top pavements are good conductors and heat absorbers in summer and can destroy permafrost. An elevated and insulated building with circulating air beneath may unbalance the thermal regime of the ground toward pergelation. Heat conductivities of some earth materials under fixed laboratory conditions are known, but the quantitative effect in nature of variable moisture conditions and of changing vegetation is not. Changes in the volume, composition, or temperature of ground water or surface runoff have effects as yet little known qualitatively or quantitatively.

All these factors must be considered to be in a delicate balance between freezing and thawing. It is to be emphasized that the thermal regime is not uniform, but changes from hour to hour, day to day, week to week, year to year, and cycle to cycle. Specifically we must think in terms of geographic position, topography, lithology, structure, and texture of soils and bedrock, hydrology, geothermal gradients, thermal conductivities, vegetation, climate (temperature, precipitation, cloudiness, wind, insolation, evaporation), and cultural features.

What effect cosmic dust clouds, changes in carbon-dioxide content of the atmosphere, inclination of the earth's axis, eccentricity of the earth's orbit, sunspots, etc., have on permafrost can be surmised only as they affect insolation and dissipation of the earth's heat.

PRACTICAL APPLICATION AND SOLUTION OF THE PROBLEMS

In a permafrost area, it is imperative that the engineer have a complete understanding of the extent, thickness, temperature, and character of the permafrost and its relation to its environment before construction of any buildings, towers, roads, bridges, runways, railroads, dams, reservoirs, telephone lines, utilidors, drainage ditches and pipes, facilities for sewage disposal, establishments for ground-water supply, excavations, foundation piles, or other structures. The practical importance of the temperatures of permafrost cannot be overemphasized.

A knowledge of whether permafrost is actively expanding, or the cold reserve is increasing, is stabilized, or is being destroyed is essential in any engineering problem. Past experience has amply demonstrated that low cost or high cost, success or failure, is commonly based on a complete understanding of the problems to be encountered. Once the conditions are evaluated, proper precautions can be taken with some assurance of success.

Muller (1945) and Liverovsky and Morosov (1941) give comprehensive outlines of general and detailed permafrost surveys as adapted to various engineering projects. These outlines include instructions for the planning of the surveys, method of operation, and data to be collected. Rarely does the geologist or engineer on a job encounter "cut and dried" situations, and it is obvious that discretion must be exercised in modifying the outlines to meet the situation at hand.

In reconnaissance or preliminary survey to select the best site for construction in an unknown area, it is recommended that the approach be one of unraveling the natural history of the area. Basically the procedure is to identify each land form or terrain unit and determine its geologic history in detail. Topography, character and distribution of materials, permafrost, vegetation, hydrology, and climate are studied and compared with known areas. Then inferences, deductions, extrapolations, or interpretations can be made with reliability commensurate with the type, quality, and quantity of original data.

Thus the solution of the problems depends primarily on a complete understanding of the thermal regime of the permafrost and active layer. No factor can be eliminated, but all must be considered in a quantitative way. It is understandable that disagreement exists on the mean annual air temperature needed to produce permafrost. Few, if any, areas actually have identical conditions of climate, geology, and vegetation; hence, how can they be compared directly on the basis of climate alone? Without doubt the mean annual temperature required to produce permafrost depends on many factors and varies at least several degrees with variations in these factors. For practical purposes, however, units (terrain units) in the same climate or in similar climates may be separated on the basis of geology and vegetation. Thus there is a basis for extrapolating known conditions into unknown areas.

The advantages of aerial reconnaissance and study of aerial photographs for preliminary site selection are manifold. Aerial photographs in the hands of experienced geologists, soils engineers, and botanists can supply sufficient data to determine the best routes for roads and railroads, the best airfield sites, and data on water supply, construction materials, permafrost, trafficability conditions, camouflage, and other problems. Such an approach has been used with

success by the Geological Survey and other organizations and individuals (Black and Barksdale, 1949; Wallace, 1948; Woods et al., 1948; Pryor, 1947).

Emphasis is placed on the great need for expansion of long-term applied and basic research projects as outlined by Jaillite (1947) and referred to by Muller (1945) for a clearer understanding and evaluation of the problems.

Recognition and prediction.—Recognition and prediction of permafrost go hand in hand in a permafrost survey. If natural exposures of permafrost are not available along cut banks of rivers, lakes, or oceans, it is necessary to dig test pits or drill holes in places to obtain undisturbed samples for laboratory tests and to determine the character of the permafrost.

Surface features can be used with considerable degree of accuracy to predict permafrost conditions if the origin of the surface forms are clearly understood. Vegetation alone is not the solution, but it can be used with other factors to provide data on surficial materials, surface water, character and distribution of the permafrost, and particularly on the depth of the active layer (Denny and Raup, unpublished manuscript; Stone, 1948; Muller, 1945; Taber, 1943a). Cave-in or thermokarst lakes (pl. 8, fig. 1), thaw sinks (Hopkins, 1949; Black and Barksdale, 1949; Wallace, 1948; Muller, 1945), and ground-ice mounds (Sharp, 1942a) are particularly good indicators of fine-grained materials containing much ground ice. Polygonal ground can be used with remarkable accuracy also if the type of polygonal ground and its origin are clearly known. Numerous types of *strukturboden*, polygonal ground, and related forms have been described and their origins discussed (Wittmann, 1950; Richmond, 1949; Çailleux, 1948; Washburn, 1947; Troll, 1944; Sharp, 1942b; Högbom, 1914). The type of ice-wedge polygon described by Leffingwell (1919) (pl. 4) can be delimited from others on the basis of surface expression. The author's work in northern Alaska (1945 to present) reveals that the polygons go through a cycle that can be described as youth, maturity, and old age—from flat surface with cracks to low-centered polygons and, finally, to high-centered polygons. Size and shape of polygons, widths and depths of troughs or cracks, presence or absence of ridges adjacent to the troughs, type of vegetation, and other factors all provide clues to the size-grade of surficial materials and the amount of ice in the ground. Frost mounds, frost blisters, icings, gullies, and many other surficial features can be used with reliability if all factors are considered and are carefully weighed by the experienced observer.

Geophysical methods of locating permafrost have given some promise (Sumgin and Petrovsky, 1947; Enenstein, 1947; Swartz and Shepard, 1946; Muller, 1945; Joestings, 1941). (See p. 282.) Various

temperature-measuring and recording devices are employed. Augers and other mechanical means of getting at the permafrost are used (Muller, 1945, and others).

Construction.—Two types of construction methods are used in permafrost areas (Muller, 1945). In one, the passive method, the frozen-ground conditions are undisturbed or provided with additional insulation, so that the heat from the structure will not cause thawing of the underlying ground and weaken its stability. In the other method, the active method, the frozen ground is thawed prior to construction, and steps are taken to keep it thawed or to remove it and to use materials not subject to heaving and settling as a result of frost action. A preliminary examination, of course, is necessary to determine which procedure is more practicable or feasible.

Permafrost can be used as a construction material (if stress or load does not exceed plastic or elastic limit), removed before construction, or controlled outside the actual construction area. Muller (1945) has shown that it is best to distinguish (*a*) continuous areas of permafrost from (*b*) discontinuous areas and from (*c*) sporadic bodies. Russian engineers recommend that in (*a*) only the passive method of construction be used; in (*b*) or (*c*) either the passive or active method can be used, depending on thickness and temperature of the permafrost. Detailed information and references on the construction of buildings, roads, bridges, runways, reservoirs, airfields, and other engineering projects (pls. 9, 10, 11, and 12) are presented by Huttl (1948); Hardy and D'Appolonia (1946); Corps of Engineers (1946, 1945); Zhukov (1946); Muller (1945); Richardson (1944); and others. Refinements of the techniques and data on Alaskan research projects (Wilson, 1948; Jaillite, 1947; Barnes, 1946) are contained largely in unpublished reports of various federal agencies.

Eager and Pryor (1945) have shown that road icings (pl. 10, fig. 3) are more common in areas of permafrost than elsewhere. They, Tchekotillo (1946), and Taber (1943b) discuss the phenomena of icings, classify them, and describe various methods used to prevent or alleviate icing.

One of the major factors to consider in permafrost is its water content. Methods of predicting by moisture diagrams (epures) the amount of settling of buildings on thawing permafrost are presented by Fedosov (1942). Anderson (1942) describes soil moisture conditions and methods of measuring the temperature at which soil moisture freezes.

Emphasis should be placed again on the fact that permafrost is a temperature phenomenon that occurs naturally in the earth. If man disturbs the thermal regime knowingly or unknowingly, he must suffer the consequences. Every effort should be made to control the thermal

regime, to promote pergelation or depergelation as desired. Generally the former is difficult near the southern margin of permafrost. If the existing climate is not cold enough to insure that the permafrost remain frozen, serious consideration should be given to artificial freezing in those places where permafrost must be utilized as a construction material. Techniques that were used at Grand Coulee Dam (Legget, 1939) or on Hess Creek (Huttl, 1948) can be modified to fit the situation. It should be borne in mind that the refrigerating equipment need be run only for a matter of hours during the summer after the ground has been refrozen and vegetation or other means of natural insulation have been employed. Bad slides on roads and railroads, settling under expensive buildings, loosening of the foundations of dams, bridges, towers, and the like probably can be treated by refreezing artificially at less cost than by any other method. In fact the day is probably not far off when airfields of Pycrete (Perutz, 1948) or similar material will be built in the Arctic where no construction materials are available.

Where seasonal frost (active layer) is involved in construction, the engineer is referred to the annotated bibliography of the Highway Research Board (1948) and to such reports as that of the Corps of Engineers (1945, 1946, 1947).

Water supply.—Throughout permafrost areas one of the major problems is a satisfactory source of large amounts of water. Problems encountered in keeping the water liquid during storage and distribution or in its purification are beyond the scope of this report. Small amounts of water can be obtained generally from melted ice or snow. However, a large, satisfactory, annual water supply in areas of continuous permafrost is to be found only in deep lakes or large rivers that do not freeze to the bottom. Even then the water tends to have considerable mineral hardness and organic content. It is generally not economical to drill through 1,000 to 2,000 feet of permafrost to tap ground-water reservoirs beneath, although artesian supplies have been obtained under 700 feet of permafrost (Dementiev and Tumel, 1946) and under 1,500 feet of permafrost (Obruchev, 1946).

In areas of discontinuous permafrost, large annual ground-water supplies are more common either in perched zones on top of permafrost or in nonfrozen zones within or below the permafrost (Cederstrom, 1948; Péwé, 1948b).

Annual water supply in areas of sporadic permafrost normally is a problem only to individual householders and presents only a little more difficulty than finding water in comparable areas in temperate zones.

Surface water as an alternate to ground water can be retained by earthen dams in areas of permafrost (Huttl, 1948).

Throughout the Arctic, however, the quality of water is commonly poorer than in temperate regions. Hardness, principally in the form of calcium and magnesium carbonate and iron or manganese, is common. Organic impurities and sulfur are abundant. In many places ground water and surface water have been polluted by man or organisms.

Muller (1945) presents a detailed discussion of sources of water and the engineering problems in permafrost areas of distributing the water. Joestings (1941) describes a partially successful method of locating water-bearing formations in permafrost with resistivity methods.

Sewage disposal.—Sewage disposal for large camps in areas of continuous permafrost is a most difficult problem. Wastes should be dumped into the sea, as no safe place exists on the land for their disposal in a raw state. As chemical reaction is retarded by cold temperatures, natural decomposition and purification through aeration do not take place readily. Large streams that have some water in them the year around are few and should not be contaminated. Promiscuous dumping of sewage will lead within a few years to serious pollution of the few deep lakes and other areas of annual surface-water supply. Burning is costly. As yet no really satisfactory solution is known to the writer. In discontinuous and sporadic permafrost zones, streams are larger and can handle sewage more easily, yet even there sewage disposal still remains in places one of the most important problems.

Agriculture.—Permafrost as a cold reserve has a deleterious effect on the growth of plants. However, as an impervious horizon it tends to keep precipitation in the upper soil horizons, and in thawing provides water from melting ground ice. Both deleterious and beneficial effects are negligible after 1 or 2 years of cultivation, as the permafrost table thaws, in that length of time, beyond the reach of roots of most annual plants (Gasser, 1948).

Farming in permafrost areas that have much ground ice, however, can lead to a considerable loss in time and money. Sub-Arctic farming can be done only where a sufficient growing season is available for plants to mature in the short summers. Such areas are in the discontinuous or sporadic zones of permafrost. If the land is cleared of its natural insulating cover of vegetation, the permafrost thaws. Over a period of 2 to 3 years, large cave-in lakes have developed in Siberia (I. V. Poiré, oral communication), and pits and mounds have formed in Alaska (pl. 10, fig. 4) (Péwé, 1948a, 1949; Rockie, 1942). The best solution is to select farm lands in those areas free of permafrost or free of large ground-ice masses (Tziplenkin, 1944).

Mining.—In Alaska, placer miners particularly, and lode miners to a lesser extent, have utilized permafrost or destroyed it as neces-

sary since it was first encountered. Particularly in placer mining, frozen ground has been the factor that has made many operations uneconomical (Wimmler, 1927).

In the early part of the century, when gold was being mined so profitably at Dawson, Fairbanks, Nome, and other places in northern North America, it was common for miners to sink shafts more than 100 feet through frozen muck to the gold-bearing gravels (P. S. Smith, unpublished manuscript). These shafts were sunk by steam jetting or by thawing with fires or hot rocks. If the muck around the shafts or over the gravels thawed, the mines had to be abandoned.

Now, with the advent of dredges, such ground is thawed, generally with cold water, one or more years in advance of operations. In the technique used holes are drilled in or through the permafrost at regular intervals of possibly 10 to 30 feet, depending on the depth and types of material, and cold water is forced through the permafrost into underlying permeable foundations or out to the surface through other holes. Hot water and steam, formerly used, are uneconomical and inefficient. Where thick deposits of overburden cover placers, they are removed commonly by hydraulicking. Summer thaw facilitates the process (Patty, 1945).

Permafrost is commonly welcomed by the miners in lode mining, as it means dry working conditions. Its effect on mining operations other than maintaining cold temperatures in the mine is negligible unless it contains aquifers. Because of cold temperatures, sealing such aquifers with cement is difficult, and other techniques must be used as the situation demands.

Some well drilling in permafrost requires modifications of existing techniques and more careful planning for possible exigencies (Fagin, 1947). Difficulty may be encountered in getting proper foundations for the rig. In rotary drilling, difficulty may be experienced in keeping drilling muds at the proper temperature, in finding adequate water supplies, or in finding proper local material for drilling muds. In shallow holes particularly, the tools will "freeze in" after a few hours of idleness. In many places refreezing of permafrost around cased holes produces pressures great enough to collapse most casing. Cementing of casings is costly and very difficult, as ordinary concrete will not set in subfreezing temperatures. Deep wells below the permafrost may encounter high temperatures (100° to 150° F.), and the hot drilling muds on returning to the surface thaw the permafrost around the casing and create a settling hazard in the foundation of the rig and also a disposal problem. In some foundations refrigerating equipment must be used to prevent settling.

Permafrost also may act as a trap for oil or even have oil reservoirs within it. The cold temperature adversely affects asphalt-base

types particularly and cuts down yields. Production difficulties and costs go up (Fagin, 1947).

Refrigeration and storage.—Natural cold-storage excavations are used widely in areas of permafrost. They are most satisfactory in continuous or discontinuous zones. Permafrost should not be above 30° F.; if it is, extreme care in ventilation and insulation must be used. Properly constructed and ventilated storerooms will keep meat and other products frozen for years. Detailed plans and characteristics required for different cold-storage rooms are described by Chekotillo (1946).

Trafficability.—In the Arctic and sub-Arctic most travel overland is done in winter, as muskegs, swamps, and hummocky tundra make summer travel exceedingly difficult (Navy Department, 1948–49; Fagin, 1947). Tracked vehicles or sleds are the only practical types. Wheeled vehicles are unsatisfactory, as most of the area is without roads.

Permafrost aids travel when it is within a few inches of the surface. It permits travel of D8 caterpillar tractors and heavier equipment directly on the permafrost. Sleds weighing many tons can be pulled over the permafrost with ease after the vegetal mat has been removed by an angle-bulldozer. Polygonal ground, frost blisters, pingos, and small, deeply incised thaw streams (commonly called "beaded" streams), rivers, and lakes create natural hazards to travel.

In areas of discontinuous and sporadic permafrost, seasonal thaw is commonly 6 to 10 feet deep, and overland travel in summer can be accomplished in many places only with amphibious vehicles such as the weasel or LVT. Foot travel and horse travel are very slow and laborious in many places because of swampy land surfaces and necessity for making numerous detours around sloughs, rivers, and lakes.

Military operations.—Permafrost alters military operations through its effects on construction of airbases, roads, railroads, revetments, buildings, and other engineering projects; through its effects on trafficability, water supply, sewage disposal, excavations, underground storage, camouflage, explosives, planting of mines, and other more indirect ways (Edwards, 1949; Navy Department, 1948–49). Military operations commonly require extreme speed in construction, procuring of water supply, or movement of men and material. Unfortunately it is not always humanly possible to exercise such speed (Fagin, 1947). Large excavations require natural thawing, aided possibly by sprinkling (Huttl, 1948), to proceed ahead of the earth movers. Conversely, seasonal thaw may be so deep as to prevent the movement of heavy equipment over swampy ground until freeze-up. Or, similarly, it may be necessary in a heavy building to steam-jet piles into permafrost and allow them to freeze in place before loading

them. These tasks take time, and proper planning is a prerequisite for efficient operation.

Camouflage is a problem on the tundra. Little relief or change in vegetation is available. Tracks of heavy vehicles or paths stand out in marked contrast for years. It is easy to see in aerial photographs footpaths and dog-sled trails abandoned 10 years or more ago.

Mortar and shell fire, land mines, shaped charges, and other explosives undoubtedly respond to changes in the character of permafrost, but no data are available to the author.

FUTURE RESEARCH NEEDED

Throughout the foregoing pages brief reference is made to aspects of permafrost or effects of permafrost on engineering, geologic, biologic, and other scientific problems for which few factual data are available. However, in the event that the reader has received the impression that a great deal is known of permafrost, it is pointed out that the science of frozen ground is relatively young and immature. It has lacked a coordinated and comprehensive investigation by geologists, engineers, physicists, botanists, climatologists, and other scientists. It is barely in the beginning of the descriptive stages, and only now is it receiving the world-wide attention it deserves.

As our civilization presses northward, the practical needs of construction, water supply, sewage disposal, trafficability, and other engineering problems must be solved speedily and economically. Our present knowledge is relatively meager, and trial-and-error methods are being used much too frequently. Practical laboratory experiments (Taber, 1930a, 1930b) and controlled field experimental stations, such as that at Fairbanks, Alaska (Jaillite, 1947), are needed in various situations in the permafrost areas. From these stations methods and techniques of construction can be standardized and appropriate steps taken to meet a particular situation. Such laboratories must be supplemented with Arctic research stations such as are found in the Soviet Union where more than 30 natural-science laboratories with permanent facilities and year-around basic studies in all phases of Arctic science are going on. The Arctic Research Laboratory at Point Barrow (Shelesnyak, 1948) is a start in the right direction. The academic approach must accompany the practical approach if satisfactory solution of the problem is to be found.

To name all the specific topics for future research would make this paper unduly long, as no phase of permafrost is well known. However, the author reiterates that the problems cannot be solved adequately until the phenomena of heat flow in all natural and artificial materials in the earth are understood and correlated with insolation, atmospheric conditions, geothermal gradients, and the complex sur-

face of the earth. Then, possibly, criteria can be set up to evaluate within practical limits the effect of various structures and materials on the dissipating surface of the earth. The complexities of geology (lithology, structure, and texture of soils and rock), hydrology, vegetation, and climate of the Arctic make the solution a formidable task but the research an intriguing problem for all earth scientists.

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